

Characterizing traits of coordination

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Abstract

How can one recognize coordination languages and technologies? As this report shows, the common approach that contrasts coordination with computation is intellectually unsound: depending on the selected understanding of the word “computation”, it either captures too many or too few programming languages. Instead, we argue for objective criteria that can be used to evaluate how well programming technologies offer coordination services. Of the various criteria commonly used in this community, we are able to isolate three that are strongly characterizing: black-box componentization, which we had identified previously, but also interface extensibility and customizability of run-time optimization goals. These criteria are well matched by Intel’s Concurrent Collections and AstraKahn, and also by OpenCL, POSIX and VMWare ESX.

Contents

1	Introduction	2
2	Qualifying criteria	3
3	Criteria evaluation	4
4	Problems of “coordination vs. computation”	6
5	Conclusion	9
	Acknowledgements	9
	References	9

1 Introduction

The author of this report studies a research community whose specialization is the management of software components in multi-component applications. The members of this community have agreed on a common linguistic referent for their activities in this field: the word “*coordination*”.

The main output from this community is a combination of programming languages and operating software aimed at optimizing the run-time execution of applications built by hierarchical composition of components. Example technologies whose authors self-identify as “working on coordination” include S-NET [16, 4], AstraKahn [17] and Intel’s Concurrent Collections (CnC) [10, 2].

A recurring theme in the discussions within this community and with external observers is whether and how much coordination differs from other forms of programming. This topic is usually introduced with either of two questions: “what is coordination exactly?” and “what distinguishes research on coordination from other research on programming language design and implementation?”

As it happens, different answers are used in these conversations depending on who is asking, who is answering and the topic at hand. This author has observed a consensus in the community that these answers are all *accepted* by the researchers as valid descriptions of their line of work.

Of these explanations, we can recognize four groups:

- *self-referential* explanations: a research activity is considered related to “coordination” if it self-identifies as such. For example, “this language is a coordination language because its designers call it a coordination language”;
- *negative space* explanations: an existing field of study is selected *ad hoc*, then a research activity is considered related to “coordination” if it self-identifies as “not related to” the selected research. For example, “this language is a coordination language because its designers do not focus on software modeling” (or functional programming, or model checking, etc.);
- *void* explanations: a word is selected *ad hoc* with no well-defined meaning, then a research activity is considered related to “coordination” if it self-identifies as “not related to” the selected word. For example, “this language is a coordination language because its designers do not intend it to be a computation language” without a clear definition for the word “computation” (cf. section 4);
- explanations *by qualification*: some well-defined, objective, observer-independent criteria on programming languages and operating software are identified, then “coordination” is defined based on the criteria. For example, “this language is a coordination language because it offers facilities to assemble applications from black-box components”, together with a careful definition of “black-box component”, constitutes a qualified explanation.

The self-referential, negative space and void explanations are, by construction, factually vacuous: a newcomer audience exposed to them will not learn anything about *what the researcher using the explanation actually does in their work*. At best, the audience may understand that the researcher needs a keyword to motivate specialized attention and funding, but not more. These forms of explanations are thus not further considered here.

Instead, this report reviews the criteria where consensus exists in the community that they can be used to recognize coordination objectively.

The discussion is presented in two parts. In section 2, we identify and detail the objective criteria that have been previously named and used by members of the research community. We then examine in section 3 how well this community’s technology matches their self-selected criteria, and also how well other technologies match the same criteria. We then use this analysis to isolate which criteria most strongly characterize the work of these researchers. Separately, in section 4 we examine the arguments that oppose “coordination” to “computation”, and we analyze how much objective understanding can be extracted from them. We then conclude in section 5.

2 Qualifying criteria

We reuse below the definition of “component” and component-based design from [1, 15]: components are defined by their interface, which specifies how they can be used in applications, and one or more implementations which define their actual behavior. The two general principles of component-based design are then phrased as follows. The first is interface-based integration: when a designer uses a component for an application, he agrees to only assume what is guaranteed from the interface, so that another implementation can be substituted if needed without changing the rest of the application. The second is reusability: once a component is implemented, a designer can reuse the component in multiple applications without changing the component itself.

Based on this definition, the word “coordination” is only used in the context of languages and infrastructures that enable component-based design¹.

Separable provisioning (Sp): the language and its infrastructure enable the reuse of components provided by physically separate programmers, and where the considered technology is the only communication means between these providers. For example, a technology that offers the ability to build a specification from different files matches this criterion.

Interface extensibility (Ie): the infrastructure enables an application designer to redefine and extend component interfaces independently from component providers, and extended interfaces can influence execution. For example, a technology that offers the ability to annotate a component to indicate *post hoc* that it is functionally pure (without state and deterministic), e.g. via a pragma or metadata, and which can exploit this annotation to increase execution parallelism, matches this criterion.

Separable scheduling (Ss): the programmer can delegate to the technology the responsibility of choosing when (time) and where (space/resources) to execute concurrent component activities. A different but equivalent phrasing for the same criterion is the ability given to a programmer to define a partial scheduling order between component activities, and ability given to the technology to decide arbitrary actual schedules as long as the partial order is respected.

¹arguably, most contemporary programming technologies already enable component-based design; however we explicitly state the requirement to clearly scope the discussion.

For example, a language where programmers can declare a data-parallel operation and where the infrastructure decides how to schedule the operation matches this criterion.

Adaptable optimization (Ao): the technology provides run-time optimization mechanisms that can adapt to different execution environments without changing the application specification. For example, a technology which can decide different placements when faced with different amounts of parallelism in hardware matches this criterion, and so does a technology able to decide different schedules over time when faced with different constraints on data locality (e.g. cache sizes).

Customizable optimization goals (Cog): the application designer can specify different optimization goals at run-time (or no earlier than when the specification work has completed) and the technology chooses different execution strategies based on them. For example, a technology which enables to select between “run fast” and “use less memory” during execution matches this criterion.

Black-box componentization (Bb): the application designer can specify an application using components only known to the technology by name and interface, and the technology provides a run-time interfacing mechanism previously agreed upon with component providers to integrate the components. For example, a technology which can link component codes compiled from different programming languages without requiring link-time cross-optimization matches this criterion. This is the main criterion proposed in [15].

Exploitable Turing-incompleteness (Eti): the specification language is not Turing complete but can still be used to define interesting / useful applications. For example, a technology whose advertised specification language can only define static acyclic data flow graphs of components matches this criterion.

3 Criteria evaluation

We evaluate in table 1 how much different technologies match the criteria defined above: the criterion are listed in columns, the technologies in rows, each intersection states whether the technology matches the criterion, and a score column at the right side sums the number of criterion matched. Arrows in the score columns indicate the rows with highest scores.

We review both technologies that self-identify as “coordination”, including S-NET and CnC named previously, and other technologies that do not identify as such: various C and C++ implementations, Glasgow Haskell, Single-Assignment C (SAC), the standard Unix shell in a POSIX environment and VMWare ESX.

While constructing table 1, we highlighted the following:

- *granularity*: each technology may offer multiple levels of component granularities, and may not match the same criteria depending on the granularity considered. For example, the C language offers black-box componentization for entire functions but not for individual statements. To reflect this,

Technology	Variant	Granularity	Criteria							Scores		
			Sp	Ie	Ss	Ao	Cog	Bb	Eti	Total	I only	
S-NET [16, 4]	no filters / star	boxes	I		I	I			I		4	4
		networks			I	I					2	2
		boxes	I		I	I			I	E	5	4
S+NET [14, 13]	no trans. / star	boxes	I		I	I		I			5	5
		networks			I	I		I			4	4
		boxes	I		I	I		I		E	6 ←	5
AstraKahn [17]		boxes	I	I	I	I		I			6 ←	6 ←
		networks			I	I		I			3	3
CnC [10, 2]		steps	I	I	I	I		I			6 ←	6 ←
C [6, 8, 12, 9, 5]		freestanding functions	I						I	E	3	2
		freestanding statements	I		E	E				E	4	1
		freestanding expressions	I	I	E	E				E	5	2
		OpenMP statements	I	I	I	I				E	5	4
		OpenCL kernels	I	I	I	E	E		I		6 ←	4
		ISO11, hosted threads	I		I	E			I		4	3
		ISO99, POSIX threads	I	E	I	E	E		I		6 ←	3
		ISO99, POSIX processes	I	I	I	I	I		I		6 ←	6 ←
C++ [7]	ISO11, POSIX	classes	I	I	E	E	E			5	2	
Haskell [11]		GHC functions	I	I	I	I			I		5	5
		GHC packages	I	I	I	I					4	4
SAC [3]		functions	I	I	I	I			I		5	5
		modules	I		I	I					3	3
Unix shell [5]	POSIX	processes	I	I	I	I		I		6 ←	6 ←	
VMWare ESX		virtual machines	I	I	I	I		I		6 ←	6 ←	

Table 1: How various technologies match the proposed criteria.

multiple rows with different granularities are used for each technology in the table.

- *intent*: a technology may happen to match a criterion although this match was not primarily intended by its designers. For example, a freestanding implementation of the C language (without library) happens to be Turing incomplete and still quite useful, although this was arguably not intended by its designer (nor commonly known of its users). To reflect this, we use the letters “I” (by intent) and “E” (emergent) at each intersection and provide two score columns in the right side.

From this first evaluation table we observe the following.

First, separable provisioning (Sp) is generally prevalent. Although it is a prerequisite to component-based design and thus coordination, its availability in a particular technology does not predict its score in our table. Therefore, it is a poor criterion to characterize coordination.

Similarly, separable scheduling (Ss) and adaptable optimization (Ao) are also relatively prevalent. Although the benefits of separate scheduling and adaptable optimization wrt. performance speedups on parallel hardware is often used to highlight the benefits of coordination, other technologies which do not self-identify as “coordination” (e.g. Haskell, OpenCL, SAC) also exhibit these features and can reap their associated benefits. These criteria may thus be phrased as “prerequisites” to recognize coordination but they are not characterizing.

Also, the “exploitable Turing-incompleteness” (Eti) criterion is, perhaps surprisingly, difficult to match. The main reason, which we outline in section 4, is that it is actually quite difficult to design a programming language which is not Turing-equivalent.

Finally, the table reveals that none of the proposed criteria clearly separates technology that self-identify as “coordinating” from those that don’t. The evaluation of whether a technology can be considered as coordination cannot yield a

Technology	Variant	Granularity	Criteria			Scores	
			Ie	Cog	Bb	Total	I only
S-NET		boxes			I	1	1
		networks				0	0
S+NET		boxes		I	I	2	2
		networks		I		1	1
AstraKahn		boxes	I	I	I	3 ←	3 ←
		networks		I		1	1
CnC		steps	I	I	I	3 ←	3 ←
C		freestanding functions			I	1	1
		freestanding statements				0	0
		freestanding expressions	I			1	1
		OpenMP statements	I			1	1
		OpenCL kernels	I	E	I	3 ←	2
		ISO11, hosted threads			I	1	1
		ISO99, POSIX threads	E	E	I	3 ←	1
		ISO99, POSIX processes	I	I	I	3 ←	3 ←
C++	ISO11, POSIX	classes	I	E		2	1
Haskell		GHC functions	I		I	2	2
		GHC packages	I			1	1
SAC		functions	I		I	2	2
		modules				0	0
Unix shell	POSIX	processes	I	I	I	3 ←	3 ←
VMWare ESX		virtual machines	I	I	I	3 ←	3 ←

Table 2: How various technologies match the proposed criteria (simplified).

boolean value and instead lies on a spectrum of “more or less able to coordinate”.

From these observations, we can select the criteria most strongly matched by these technologies that the researchers would like to objectively describe as “strongly coordinating.” This suggests the criteria Ie, Cog and Bb and the summary in table 2. As the table shows, AstraKahn, CnC, OpenCL, POSIX and VMWare ESX can be considered strongly coordinating, each at their preferred component granularity: boxes, steps, kernels, threads/processes and virtual machines, respectively.

4 Problems of “coordination vs. computation”

During the discussions around coordination, this author has observed a prevalent use of the following arguments by the members of the community:

1. “**coordination technologies can be distinguished from computation technologies**”;
2. “**what differentiates coordination and computation technologies is the intent of the designer: the designers of coordination languages do not focus on computation**”;
3. “**there exist ‘pure’ coordination languages that cannot be used to specify computations.**”

All three arguments are motivated by a subjective, human desire of the involved individuals, that to create a “us-versus-them” vision of the research. The ulterior motive is to generate specialized attention and attract dedicated funding. In fairness to this community, we highlight here that this ulterior motive is shared by most academic researchers regardless of their field of study.

However, despite and regardless of the motive and its subjectivity, the individuals involved claim (both implicitly and explicitly) that these three arguments can be recognized as objective by an external observer, i.e. they can stand and be defended at face value.

What interests us here is that all three arguments require some shared understanding of what is meant by “computation.” If no shared understanding can be found, then all three arguments are void and thus intellectually irrelevant.

Moreover, if a shared understanding can be found, then only argument #3 is objectively qualified. Even with a shared understanding of computation, arguments #1 and #2 remain at best “negative space” arguments (cf. section 1) and still do not inform about what coordination actually entails.

To see how much of argument #3 can be “saved” for the purpose of objective discussions, we need to investigate two points. The first is how much shared understanding can be gathered around the term “computation”. The second is whether, assuming some shared understanding of what “computation” entails, argument #3 actually holds: that languages that cannot express computation actually exist, and can be called coordination languages.

4.1 About the notion of computation

As of this writing, there exists no formal definition of what constitutes a computation in general. What is known empirically is that for any function of mathematics it is often possible to build a machine which can calculate the value of this function for some input. What is known formally, is that for any given number function of mathematics it is always possible (in theory) to build a machine that can calculate the value of this function. What is not known however, is the set of all mathematical functions a given concrete (real-world) machine can reproduce; and whether it is possible to build a machine for all possible mathematical functions, not only number functions. Meanwhile, people can be observed to also build machines to perform work that is not described formally but is still considered useful.

In this context, two approaches can be taken to define “computation”. One can seek formalism at all costs, and restrict the shared understanding to Church and Turing’s *thesis*: that the set of computations is exactly the set of all possible input-output transformations by any theoretical Turing machine. However, this Manichean approach excludes a range of machine activities that are commonly considered to be “computations” in practice, too: transformation and communication of real (physical) variables, non-deterministic operations over parallel hardware with loosely synchronized time, ongoing processes without a start event, etc.

The other way to define “computation” is to identify some useful real-world artefacts and behaviors, call them “computation” axiomatically, then reverse-engineer which languages and formal systems can be used to specify them. There are multiple ways to do so; here are the two such definitions that seem to gather most consensus:

- “*terminating value computations*”: any operation which consumes a *finite supply of static data* as input, runs for a *finite amount of time* and produces a *finite supply of static data* as output. This includes but is not limited to the observable behavior of halting Turing machines;
- “*process computations*”: any operation which is running within a *well-formed space boundary* (e.g. a specific component of a machine), running at a *measurable cost* and that is *controllable*: where an external agent (e.g. a person or another system) can start, stop, observe, accelerate, slow (etc.) the operation.

Chosen definition for “computation”	Computation-less languages	Incomplete computation languages
Behavior of Turing machines	(none known)	few languages, but includes C
Terminating value computations	(none known)	most languages
Process computations	some declarative languages, including Prolog, pure λ -calculus, HTML	most languages

Table 3: Languages that cannot specify computations.

The choice of approach also defines the objective substance of any discussion that capitalizes on the notion of computation. Different choices result in different, possibly conflicting understandings. Therefore, any situation where the word “computation” is used casually to support negative space arguments should be reviewed with critical care; in particular, one should feel challenged to isolate and clarify explicitly what assumptions are being made.

4.2 Languages that “cannot specify computations”

There are two interpretations for the phrase “cannot specify computations”: either “cannot specify *any* computation” or “cannot specify *all* computations”. The argument “There exists pure coordination languages that cannot specify computation” thus defines two classes of languages: *computation-less* languages which cannot be used to define any computation whatsoever; and *incomplete* languages which can only be used to specify a limited subset of computations.

Both can only be discussed in the context of a specific, *a priori* chosen understanding of the word “computation” as described in the previous section. We collate in table 3 a condensed inventory of existing programming languages that are either computation-less or incomplete for the various definitions of “computation” isolated previously.

Table 3 enables three observations.

The first is that it is difficult to find concrete computation-less languages, for any definition of “computation”. In general, it is actually difficult to design a computation-less language: any language that is able to define a dynamic evaluation that can react to state, regardless of how dynamic its input is, can be tricked at a higher-level to define *some* computations. For example, with S-NET one can define operations using Peano arithmetic on the depth of the run-time expansion of a “star” combinator over a synchrocell, using only record types to perform choices. A computation-less language should either prevent its user from defining a dynamic evaluation, or restrict the evaluation to be state-insensitive (or both). It is debatable whether languages with such restrictions can be called “programming” languages at all.

The second is that if we consider process computations in general and we understand that “pure coordination languages are those languages that are computation-less”, we would need to accept languages like Prolog, λ -calculus or HTML as coordination languages. This does not appear compatible with the vision of the coordination community being studied.

The third is that there are “too many” languages that are incomplete with regards to each definition of “computation” to hold a strong us-versus-them argument. For the two informal definitions, i.e. terminating value computations and process computations, if we understand that “pure coordination languages are those languages that are incomplete with regard to specifying computa-

tion”, then virtually any programming language in use today is a coordination language. If we take the formal definition instead (Turing-incompleteness), then C would also qualify as a coordination language because C is also Turing-incomplete². Again, this does not appear compatible with the vision of this community.

To summarize, it may not be possible to use argument #3 successfully to motivate specialized attention to the work of this community.

5 Conclusion

We have reviewed in this report the commonly used, subjective argument that “coordination can be contrasted to computation”. We have revealed that this argument and all currently used related phrasings are largely intellectually unsound and we conclude they cannot be used to support specialized scientific attention towards “coordination” as a research activity.

Instead, we have highlighted that research on “coordination” can be supported objectively using motivating arguments based on objective criteria. Of the various candidate criteria that have been proposed so far, we have shown that only three characterize the work of the researchers involved:

- *interface extensibility*: the ability to extend or replace component interfaces arbitrarily after components are provided, and define valid composite behavior using the modified interfaces even if they conflict with the internal structure of the components;
- *customizable optimization goals*: the ability to specify different optimization goals after the application has been specified, e.g. during execution, and the ability of the technology to use different execution strategies to match the custom goals;
- *black-box componentization*: the ability to specify composite applications from components only known by name and interface, and the existence of run-time interfacing mechanisms that do not require the coordination technology to know anything about the internal structure of components.

Of these three criteria, we had previously [15] identified the last as a clear objective criterion to recognize coordination, and we had recognized that programming technologies are “more or less coordinating” depending on how well they match the criterion. In the present report, we have extended this argument to the other two criteria, and recognized several concrete coordination technologies: AstraKahn and Intel’s CnC, but also OpenCL, POSIX and VMWare ESX.

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²we consider here the C language without its standard library as defined in [6, 8]. This author can provide a demonstration of C’s Turing-incompleteness upon request.

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